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13. ABSTRACT (Maximum 200 words)

This project was primarily aimed at building a suite of real-time interactive nonlinear pde simulators in order to investigate control, chaos synchronization and message encoding in different classes of semiconductor and fiber laser systems. Kenton White, who is currently employed by Nortel Networks, was the initial recipient of funding. Mr. White made significant progress on understanding the role of multi-longitudinal modes in influencing the chaotic dynamics of semi-conductor lasers under weak external optical feedback and/or injection, and how messages could be encoded in a wavelength division multi-flexed format by injection of each message into a separate chaotic laser mode. This work has been the basis for building a truly interactive simulation environment for the study of complex long scale dynamical behavior of semi-conductor lasers in isolation and as components of a more complex integrated optics system. Two graduate students, Kevin Gross and David Scherer, were supported on a split basis over the past two years, including the one-year extension. Funding under the main contract, enabled us to build an object-oriented simulation environment. Mr. Gross started a project that studies the control of spatiotemporal chaotic behavior in a wide aperture single longitudinal mode semi-conductor laser. Mr. Gross developed his own pde solver to integrate the semi-conductor CSH equation directly. David Scherer, a second year graduate student, studied the stability of DFB lasers to perturbations introduced during the process of fabrication. Mr. Scherer used the interactive device simulator, developed under the main contract, to map out stability regimes of DFB lasers with cleaved-cleaved, AR-cleaved, and HR/AR facets. The work carried out under this project enabled the development of a fully interactive pde simulator that runs on a fast PC. The simulator uses an extremely efficient digital filter-based algorithm to rapidly evolve the internal optical and carrier fields in the device. The simulator reads in pre-computed rigorous semi-conductor material optical gain and refractive index tables. Complex optical systems including semi-conductor amplifier/laser and fiber amplifier/laser modules form the basic building blocks of the simulator. External optics such as mirrors, beam splitters, wavelength filters, etc. can be easily attached to the system. GUI viewers allow the user to look into the semiconductor laser and fiber device to study internal fields as the simulation is running. Other viewers process data on-the-fly to produce output power time series, evolving power spectra, eye-diagrams, etc.

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AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT) REPORTING FORM

The Department of Defense (DoD) requires certain information to evaluate the effectiveness of the AASERT program. By accepting this Grant which bestows the ASSERT funds, the Grantee agrees to provide 1) a brief (not to exceed one page) narrative technical report of the research training activities of the AASERT-funded student(s) and 2) the information should be provided to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1. Grantee identification data: (R&T and Grant numbers found on Page 1 of Grant)

a. University of Arizona (FRS 300780)
University Name

b. F49620-97-1-0451
Grant Number

c.
R&T Number

d. J. V. Moloney
P.I. Name

e. From: 1 Sept 00 To: June 30 01
AASERT Reporting Period

NOTE: Grant to which AASERT award is attached is referred to hereafter as "Parent Agreement".

2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

a. Funding: $52,100

b. Number FTEGS: 1.0

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month award.

a. Funding: $0

b. Number FTEGS: 0

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

a. Funding: $21,948

b. Number FTEGS: 1.0

c. Number UGS: 1

VERIFICATION STATEMENT: I hereby verify that all students supported by the AASERT award are U.S. Citizens.

Principal Investigator

12/18/01
Date

University of Arizona
F49620-97-1-0451

-J. Long, SPS 12/19/01

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1 Sept 2000 to 1 May 31 2001
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Interactive Nonlinear PDE Simulators

Arizona Center for Mathematical Sciences
Department of Mathematics
University of Arizona
PI: J.V. Moloney

The Arizona Center for Mathematical Sciences is currently involved in modelling the complex dynamics of semiconductor amplifiers and lasers. This project involves large scale computation utilizing an in-house dedicated computational facility funded under DURIP awards. The main contracts supporting this research over the span of the current AASERT grant are AFOSR-F49620-97-1-0002, "High Speed Modulation, Beam Steering and Control of Spatiotemporal Chaos in Semiconductor Lasers" and AFOSR-F49620-00-1-0002, "Semiconductor Amplifier and Laser Wavelengths: From Microscopic Physics to Device Applications"

This project was primarily aimed at building a suite of real-time interactive nonlinear pde simulators in order to investigate control, chaos synchronization and message encoding in different classes of semiconductor and fiber laser systems. Kenton White, who is currently employed by Nortel Networks, was the initial recipient of funding under the present AASERT. He made significant progress on understanding the role of multi-longitudinal modes in influencing the chaotic dynamics of semiconductor lasers under weak external optical feedback and/or injection. Kenton made significant strides understanding how messages could be encoded in a wavelength division multiplexed format by injection of each message into a separate chaotic laser mode. He observed a new form of "quasi-synchronization" whereby some channels would remain synchronized (absence of a "one" bit perturbation) while others would transiently lose synchronization (presence of a one bit knocks the system off the chaotic attractor for a short while). This work has been the basis for building a truly interactive simulation environment for the study of complex long scale dynamical behavior of semiconductor lasers in isolation and as components of a more complex integrated optics system. Kenton's publications are listed at the end of this report[1-3].

Two graduate students, Kevin Gross and David Scherer, were supported on a split basis over the past two years, including the one –year extension of this AASERT. Funding under the main contract above, enabled us to build an object-oriented simulation environment. Both students played central roles in designing some of the basic algorithms and applying the simulator to a variety of problems. Kevin started a project that studies the control of spatiotemporal chaotic behavior in a wide aperture single longitudinal mode semiconductor laser. The first phase of this work required the development of a method for extracting the coefficients of a Swift-Hohenberg amplitude equation from microscopic gain/refractive index tables, computed for specific material compositions and Quantum Well geometries. He developed his own pde solver to integrate the semiconductor CSH equation directly. David Scherer, a second year graduate student, studying the stability of DFB lasers to perturbations introduced during the process of fabrication. The very

low yields, and consequently the high cost of these lasers derives form the fact that it is extremely difficult to match the Bragg grating length to the actual cavity length. A mismatch of a fraction of a micron at either end of the cavity can significantly influence laser performance. David used the interactive device simulator, developed under the main contract, to map out stability regimes of DFB lasers with cleaved-cleaved, Ar-cleaved and HR-AR facets.

The work carried out under this project enabled the development of a fully interactive pde simulator that runs on a fast PC. The simulator uses an extremely efficient digital filter-based algorithm to rapidly evolve the internal optical and carrier fields in the device[4]. The simulator reads in pre-computed rigorous semiconductor material optical gain and refractive index tables[5]. Complex optical systems including semiconductor amplifier/laser and fiber amplifier/laser modules form the basic building blocks of the simulator. External optics such as mirrors, beam splitters, wavelength filters etc can be easily attached to the system. GUI viewers allow the user to look into the semiconductor laser and fiber device to study internal fields as the simulation is running. Other viewers process data on-the-fly to produce output power time series, evolving power spectra, eye-diagrams etc. The simulation environment is being used for research by four new graduate students who began their studies this past Fall.

The following two examples illustrate the general robustness and functionality of the optical system simulator (OSS). The first example is of a gain-clamped semiconductor optical amplifier that utilizes a DFB laser with its emission wavelength strongly detuned from gain peak. The carrier density in the running laser is approximately clamped. Weak injected signals with wavelengths outside the DFB grating reflection bandwidth, exhibit near linear amplification over a broad range of input powers. The idea is to run this system as a WDM amplifier with each signal representing a separate channel. The picture below shows the DFB laser gain and wavelength at the "average" clamped carrier density. The signal channels are strongly amplified (15dB) and show excellent linearity over a range of total signal output powers.

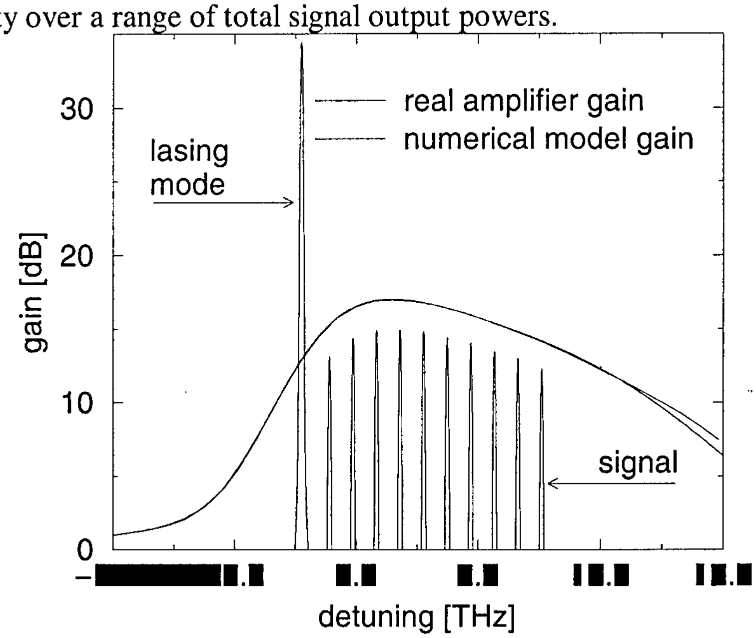


Figure 1. Gain-clamped DFB semiconductor optical amplifier gain, lasing wavelength and input

WDM signals.

In order to test the linear amplifier response of the system, we injected a detuned signal into the running DFB laser and monitored the output sign al power. The following figure shows a graph of the output power versus amplifier gain for the system.

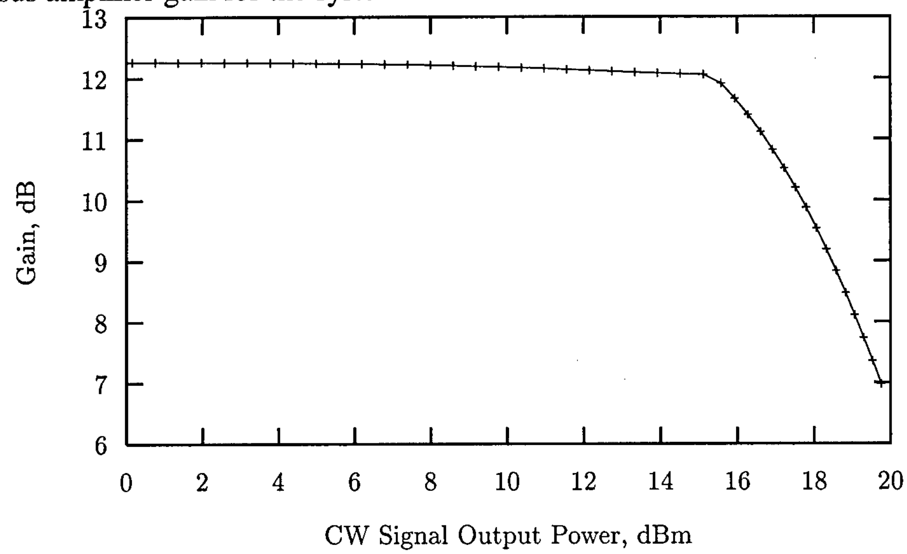
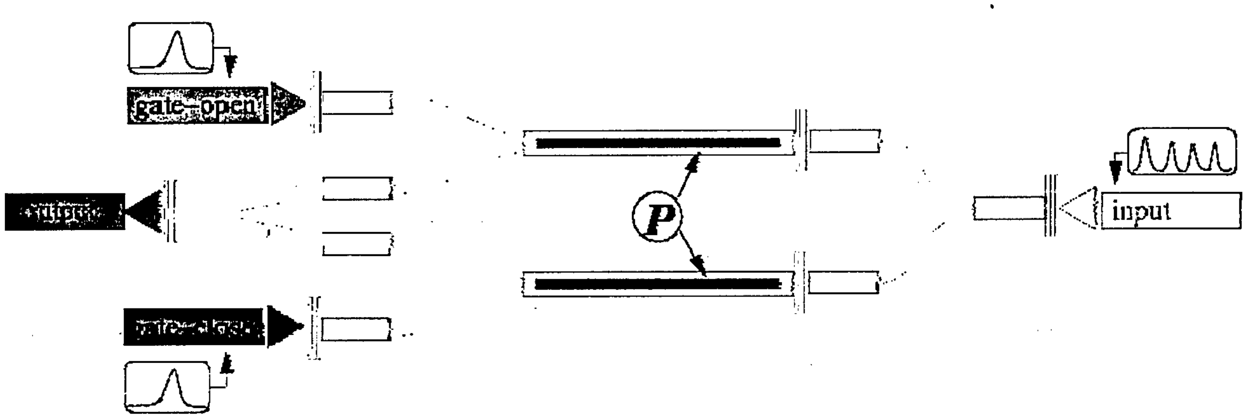


Figure 2. Plot of SOA gain versus amplified output power.

The device shows excellent linearity over a wide range of output powers. The roll-over at higher output power is a result of strong interaction with the DFB lasing mode. Having established the good linear amplifying properties of the SOA, we then built a simulation of a Mach-Zehnder interferometer (MZI) that all-optically samples multi-Gbit input streams of data. The overall geometry of the MZI is sketched below.



This complex device is an excellent illustration of a multi-component optical processing system. The basic structure contains an SOA in each interferometer arm. The SOAs are set up so that both arms are out of phase initially. Bit streams in the input data stream on the right suffer

destructive interference and no signal passes through the output. If the data is a multi-Gbit time division multiplexed message stream, then the data can be demultiplexed using a sequence of picosecond (18 ps) gate pulses input from the left. An individual channel can be extracted by firing the gate pulses in rapid sequence at a repetition rate corresponding to the channel time separation. This whole system is designed using the microscopically calculated semiconductor dielectric response as input to the simulator. The action of the gate pulses in extracting data bits (pulses) is illustrated in the next figure.

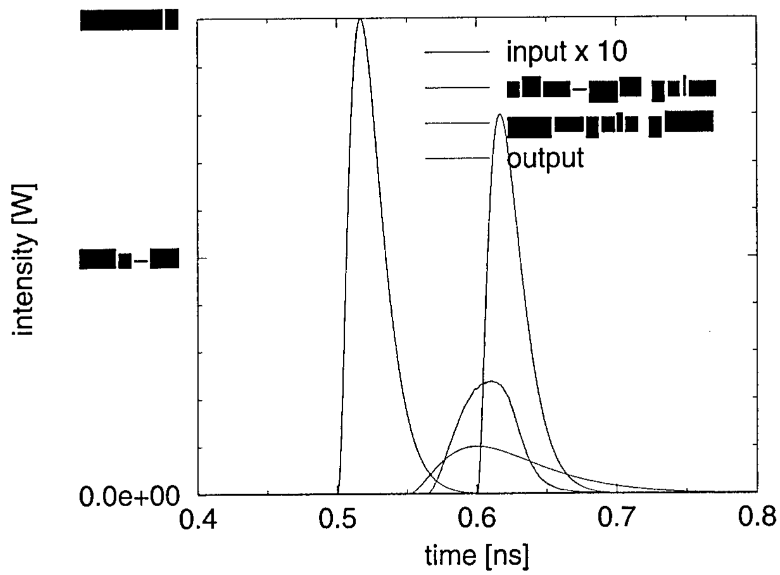


Figure 3. Demultiplexing of a multi-Gbit data stream encoded as short optical pulses.

The first gate pulse (top left) phase matches both arms of the MZI and the bottom gate pulse phase mismatches the arms again. This fast sequencing of gates pulses beats the rather sluggish nanosecond recovery of the carrier density and enables much faster data processing. The low amplitude pulse (solid curve) from the input stream is amplified and distorted by the gating action (dotted curve). The device has to be carefully tuned for proper operation.

These two examples provide ample evidence that we have been able to develop an extremely sophisticated interactive nonlinear pde simulator to describe semiconductor and fiber amplifiers and lasers. The AASERT grant provided an important underpinning for the overall success of our project.

REFERENCES

1. J.K. White, J.V. Moloney, A. Gavrielides, V. Kovanis, A. Hohl, and R. Kalmus, "Multi-Longitudinal Mode Dynamics in a Semiconductor Laser Subject to Optical Injection," *IEEE JQE,* Vol. **34**(8), pp. 1469-1473 (1998)].
2. G. Huyet, J.K. White, A.J. Kent, S.P. Hegarty, J.V. Moloney and J.G. McInerney, "Semiconductor Laser with Optical Feedback: An Example of Antiphase Dynamics in a Delayed Dynamical System," *Physical Review Letters*, submitted 1998)]
3. J.K. White and J.V. Moloney, "Multi-Channel Communication Using an Infinite Dimensional Spatiotemporal Chaotic System," *Physical. Review A, **59**,*pp. 2422-2426 1999)
4. J. Hader, J.V. Moloney and S.W. Koch, "Microscopic theory of gain, absorption and refractive index in semiconductor laser materials: Influence of conduction band non-parabolicity and Coulomb-induced inter-subband coupling". IEEE J. Quant. Electron., **35**, pp 1878-1886, 1999.
5. M. Kolesik and J.V. Moloney, "A spatial digital filter method for broad-band simulation of semiconductor lasers", IEEE J. Quant. Electron., **37**, pp. 936-944, 2001.